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BRAYTON CYCLE ALTERNATOR-DRIVE TURBINE AERODYNAMIC STUDY

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TECHNICAL PAPER proposed for presentation at Intersociety Energy Conversion Engineering Conference sponsored by the Institute of Electrical and Electronics Engineers
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ABSTRACT

The principal results obtained from the study of a two-stage turbine indicated a satisfactory level of efficiency, a small Reynolds number effect, and a rather large rotor-tip-clearance effect. When applying these results to a two-shaft Brayton power system, it was found that the turbine system efficiency was actually one point higher than that designed for and did not vary significantly during operation over a wide range of pressure level and, consequently, power output.

INTRODUCTION

The NASA is currently investigating components of a Brayton cycle space power system designed for a 10-kilowatt-shaft power output. Both single shaft of current interest and two-shaft turbomachinery arrangements are being studied. The reference system, which is used in this program, is described in Ref. 1. It utilizes the two-shaft turbomachinery arrangement wherein one turbine drives the compressor and another turbine drives the alternator. This arrangement was selected because the specified alternator rotative speed of 12,000 rpm was not compatible with the high rotative speed required to obtain a compact efficient compressor. A schematic diagram of the reference two-shaft system is shown in Fig. 1.

As part of this program, aerodynamic studies have been made of a 15.25-centimeter diameter radial-inflow turbine designed to drive the high-speed compressor used in the reference system. Results of these investigations, as reported in Refs. 2, 3, and 4, have indicated efficiencies in the 85 to 90 percent range, which is quite acceptable for this application.

An experimental study of the performance of the associated alternator-drive turbine was also made to determine its performance characteristics. This turbine was a two-stage axial-flow unit with a mean diameter of 21.59 centimeters. A complete description of its design is presented in Ref. 5. The experimental investigation of this turbine had three principal objectives: (a) to establish its level of efficiency at design aerodynamic conditions, (b) to determine the effect that Reynolds number variations have on this efficiency (the design Reynolds number was rather low due to the low mass flow), and (c) to determine the effect that tip clearance has on efficiency level. The results of the investigations directed at these objectives are presented in Refs. 6, 7, and 8.

The objectives of this paper are twofold. The first objective is to review the principal results obtained during the experimental study of this alternator-drive turbine. The second objective is then to indicate the significance of these results as applied to the reference Brayton system.

SYMBOLS

N	turbine speed, rpm
p	absolute pressure, N/cm^2
Re	Reynolds number, $w/\mu r_m$
r	radius, m
T	absolute temperature, ^oK
U	blade velocity, m/sec
V	absolute gas velocity, m/sec
V_j	ideal jet speed corresponding to total-to-static-pressure ratio across turbine, m/sec
W	relative gas velocity, m/sec
w	mass flow, kg/sec
γ	ratio of specific heats
δ	ratio of inlet total pressure to U.S. Standard sea-level pressure, p_1'/p^*
ϵ	function of γ used in relating parameters to those using air inlet conditions at U.S. Standard sea-level conditions, $\frac{\gamma^*}{\gamma}\left(\frac{\gamma+1}{2}\right)^{\gamma/(\gamma-1)} \Big/ \left(\frac{\gamma^*+1}{2}\right)^{\gamma^*/(\gamma^*-1)}$

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η_s static efficiency (based on inlet-total-to exit-static-pressure ratio)

η_t total efficiency (based on inlet-total-to exit-total-pressure ratio)

θ_{cr} squared ratio of critical velocity at turbine inlet to critical velocity at U.S. Standard sea-level temperature, $(V_{cr}/V_{cr}^*)^2$

μ gas viscosity, kg/(m)(sec)

ν blade-jet speed ratio, U_m/V_j

Subscripts:

cr condition corresponding to Mach 1

m mean radius

1 station at turbine inlet

2 station at first-stage stator exit

3 station at first-stage rotor exit

4 station at second-stage stator exit

5 station at second-stage rotor exit

6 station at exhaust pipe flange

Superscripts:

' absolute total state

* U.S. Standard sea-level air conditions (temperature, 288.15° K; pressure, 10.128 N/cm^2 abs)

DESCRIPTION OF TURBINE

As indicated in the INTRODUCTION, the alternator turbine was a two-stage unit designed to develop 10-kilowatts of shaft power at 12,000 rpm. Table I presents the pertinent design requirements for this turbine as dictated by the selected cycle conditions. Argon was selected as the working fluid. The design Reynolds number of 4.95×10^4 (see symbols for definition) is substantially lower than that normally encountered. The indicated design efficiencies include an estimate of the effect of this low Reynolds number and, in addition, reflect the use of rather small rotor-blade-tip clearances during operation. A photograph of the turbine rotor is shown in figure 2.

Design Velocity Diagrams

The design velocity diagrams for the subject turbine are presented in figure 3. These diagrams were calculated from the design conditions and requirements assuming free vortex flow and an equal work split between the two stages. The diagrams indicate a conservative aerodynamic design with high reactions and low Mach numbers across all blade rows. Blade-exit-angle values are seen to be rather flat, being about 70° for all blade rows. This flat angle kept the absolute kinetic energy leaving the second stage rotor at a low level.

Blade Description

The rotor assembly shown in figure 2 included 36 blades in each of the two stages, with solidities at the mean diameter (21.59 cm) of 1.3 and 1.4. The associated first and second stage stator assemblies contained 44 and 40 blades, respectively, with mean section solidities of approximately 1.6 for both blade rows. All these blade rows were considered conventional with smoothly converging flow passages and minimum surface decelerations.

Turbine Assembly

Figure 4 presents a cross-sectional view of the alternator turbine assembly as used for the aerodynamic study. Also included are the station nomenclature, major dimensions, and positions where pertinent measurements were made. The test fluid (argon) enters the turbine through a set of inlet guide vanes, which provided a small amount of prerotation simulating that leaving the compressor-drive turbine in the actual application. After passing through the turbine, the flow is ducted into an exhaust collector, which includes a rather sharp radially-outward turn immediately downstream from the second-stage rotor. This sharp turn is favorable for a reduction in overall turbine length, but would not be expected to serve as an efficient diffuser. The turbine shaft is seen to be supported on rolling-element bearings. Figure 5 shows a photograph of this assembly with the inlet section facing the camera. The inlet guide vanes, exhaust scroll, and vertical exit duct can be clearly seen.

TEST FACILITY

A schematic diagram of the apparatus used in the performance evaluation of the subject turbine is shown in figure 6. Argon, from a high-pressure supply system, was heated, filtered, and then passed through a flow-measuring station that consisted of a calibrated flat-plate orifice. A pressure control valve upstream from the turbine regulated the turbine-inlet pressure. With a given inlet pressure, a remotely-controlled valve in the low-pressure exhaust line was used to maintain the desired pressure ratio across the turbine. The power output of the turbine was absorbed and the speed controlled by an air-brake dynamometer that was cradle-mounted on air bearings for torque measurement. Turbine torque was obtained by adding a calibrated bearing and seal friction torque to the measured overall torque. A more complete description of the apparatus, instrumentation, and procedure can be found in Refs. 6, 7, and 8.

RESULTS AND DISCUSSION

The principal experimental results of the alternator-drive turbine test program will be presented first. This will be followed by a discussion of these results as related to the reference Brayton system for which it was designed.

Experimental Results

As indicated in the INTRODUCTION, there were three phases to this program: the establishment of the turbine performance at design aerodynamic conditions, determination of the effect of Reynolds number on performance and, finally, the influence of tip clearance.

Performance at design aerodynamic conditions. - Turbine efficiency is presented in figure 7 as a function of blade-jet speed ratio over the range of speeds and pressure ratios covered. Both total and static efficiencies based on the pressure ratio from turbine inlet to the exhaust collector exit (station 6, fig. 4) are shown. At the design speed and design blade-jet speed ratio (0.465), the static efficiency is seen (fig. 7(a)) to be 0.826, which is equal to the selected design value. Figure 7(b) shows that the associated total efficiency was about 1 point lower than the design value of 0.843.

The turbine was also rated on the basis of the pressure ratio from the turbine inlet to the rotor exit. A comparison of the static efficiencies obtained at the rotor exit with those at the collector exit, for design speed and pressure ratio, showed that there was little static pressure recovery through the collector. In addition, comparison of total efficiencies showed that there was a drop of about 1 point in total efficiency in the collector. These experimental values were about the same as the design values and indicated that the collector performed as designed.

The results of the investigation also indicate that at the design point, a mass flow about 4 percent lower than design was passed. This deficiency was attributed to the throat areas of all stators and rotors being somewhat smaller than the design values. Such a deviation in flow would be expected to have only a secondary effect on the efficiency level.

Effect of Reynolds number on performance. - In a Brayton system, wide variations in power output can be accomplished through variations in the system pressure level. Since there is an associated variation in the Reynolds number, it is important to know how the component performance responds to this variation. As a consequence, the subject turbine was investigated over a range of Reynolds numbers from approximately one-third to three times the design value. This represented an order of magnitude variation in power output.

The variations in mass flow and overall total efficiency are presented in figure 8 as functions of Reynolds number. From figure 8(a) it is evident that the effect of an order of magnitude variation in Reynolds number on equivalent mass flow was minor, with the variation in flow being only approximately 6 percent. Such a variation could be easily accommodated in an actual system by either blade-setting adjustment or a slight shifting in operating conditions.

The variation in overall total efficiency of the turbine with Reynolds number at design blade-jet speed ratio and speed is shown in figure 8(b). It can be seen that over the 10-1 range in Reynolds number there was about a 6-7 point variation in efficiency. Since the design Reynolds number level was low, there had been a concern that a substantial reduction in efficiency would be encountered at the reduced Reynolds number levels. It is evident that a severe reduction in efficiency was not encountered, and the variation that did exist was consistent with that expected from turbulent-flow boundary-layer considerations within the turbine.

Tip clearance effect. - Because of the high-reaction design of the turbine, it was anticipated that tip clearance magnitude could have a significant effect on the turbine efficiency. To explore this aspect, the turbine was aerodynamically investigated at two values of clearance. The first clearance was 0.033 centimeter, representing a rather small value. All data presented up to this point were taken at that clearance. The second clearance was 0.079 centimeter, representing a value more practical in the hot machine, at least for development purposes.

The test results verified the important effect of tip clearance for this design. The overall efficiency was reduced by approximately 4 points as the clearance was increased from 0.033 to 0.079 centimeter. From these results it is evident that it would be highly desirable to hold the clearances at a minimum. Since the rotor blading stresses are low, an alternate configuration using rotor-tip shrouds might be more desirable since this type of configuration results in substantially lower loss for the same running clearance.

Application of Results to Reference Brayton System

Having established the pertinent performance characteristics of the alternator-drive turbine, it is now possible to obtain the efficiency level of the turbine system as a whole for the reference Brayton space power application. This turbine system includes the following:

(a) the radial-inflow turbine designed to drive the compressor (refs. 2 and 3)
(b) the transition section between the compressor-drive turbine and the subject alternator-drive turbine (ref. 4)
(c) the subject alternator-drive turbine.

The turbine-system efficiency was computed based upon the total to total pressure ratio from the compressor-drive turbine inlet to the alternator turbine exhaust-collector outlet. The resulting turbine-system efficiencies are shown in figure 9 for a range of shaft-power outputs from 3 to 30 kilowatts (design is 10). Two curves are shown, one for each of the rotor tip clearances. Approximately $1\frac{1}{2}$ points separates these curves, thus reflecting the relatively small contribution of alternator-drive turbine work to total turbine work.

Considering now only the small-clearance curve, it can be seen that at the design condition of 10 kilowatts the turbine-system efficiency is 0.86, which is slightly higher than that assumed (0.85) in the reference system. Therefore, this efficiency level is quite satisfactory. As power increases from 3 to 30 kilowatts, the turbine-system efficiency increases from 0.84 to 0.88. An effect of this variation on cycle efficiency can be obtained from Ref. 1, where it was indicated that for fixed solar collector and radiator sizes, a 1 point change in turbine-system efficiency resulted in approximately a 1 point (4-5 percent relative) change in cycle efficiency. Thus, over the tenfold range of power considered, the cycle efficiency change due to the turbine-system efficiency variation would be approximately 4 points. If the radiator could be resized for each power level within the range of interest, then the cycle efficiency variation could be made even smaller.

CONCLUDING REMARKS

This paper has summarized the principal results obtained during the aerodynamic investigation of a two-stage turbine designed as the alternator drive in a two-shaft space Brayton power system. The experimental results indicated a satisfactory level of efficiency, a small Reynolds number effect, and a rather large rotor-tip clearance effect. The tip-clearance effect indicated that either small clearances or a shrouded design would be desirable.

When applying these results to the reference Brayton system, it was found that the overall turbine-system efficiency, where the turbine system refers to both the compressor-drive and alternator-drive turbines as well as the transition section between the two, was one point higher than that designed for. For an order of magnitude change in pressure level and, consequently, power output, results indicated that the variation in turbine system efficiency was rather small and would not cause any major changes in cycle efficiency.

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7. Nusbaum, W. J., and Kofskey, M. G., "Experimental Performance Evaluation of an 8.5-Inch- (21.59-cm-) Mean-Diameter Axial-Flow Turbine at Reynolds Numbers from 18 000 to 177 000," NASA TN D-4432, 1968.

8. Kofskey, M. G., and Nusbaum, W. J., "Performance Evaluation of a Two-Stage Axial-Flow Turbine for Two Values of Tip Clearance," NASA TN D-4388, 1968.

TABLE I. - TURBINE DESIGN VALUES

Working fluid	Argon
Inlet total temperature, T_1', ^oK	936.11
Inlet total pressure, p_1', N/cm^2	5.826
Outlet total temperature, T_6', ^oK	869.0
Outlet total pressure, p_6', N/cm^2	4.663
Mass flow, w, kg/sec	0.277
Turbine rotative speed, N, rpm	12000
Overall total to total efficiency, η_t	0.843
Overall total to static efficiency, η_s	0.826
Blade-jet speed ratio, ν	0.465
Reynolds number, $Re = w/\mu r_m$	4.95×10^4

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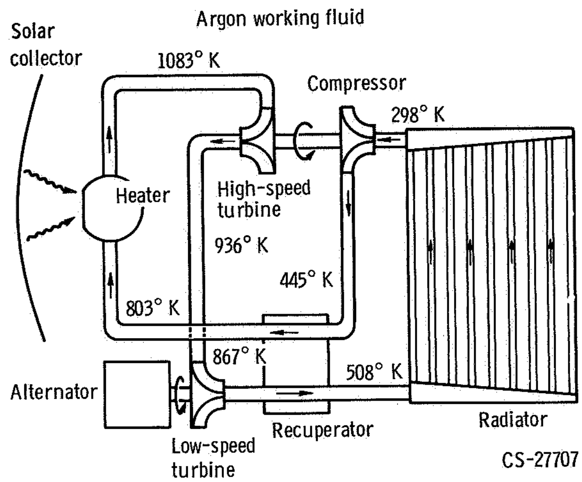

Figure 1. - Schematic diagram of two-shaft Brayton cycle system.

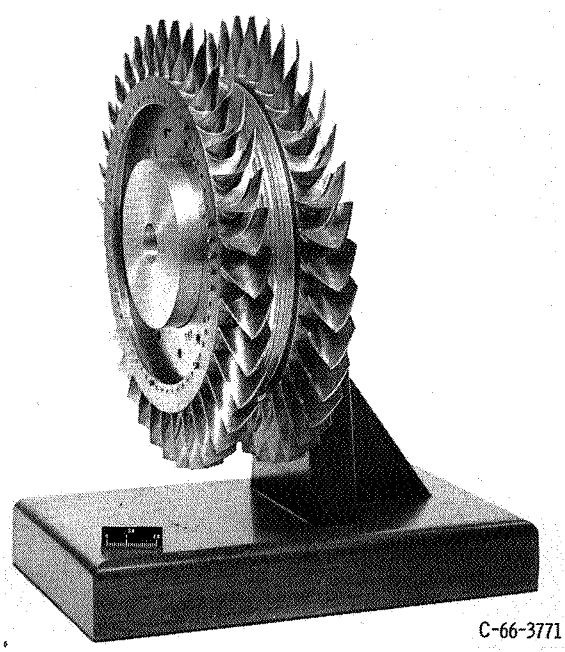

Figure 2. - Two-stage turbine rotor assembly.

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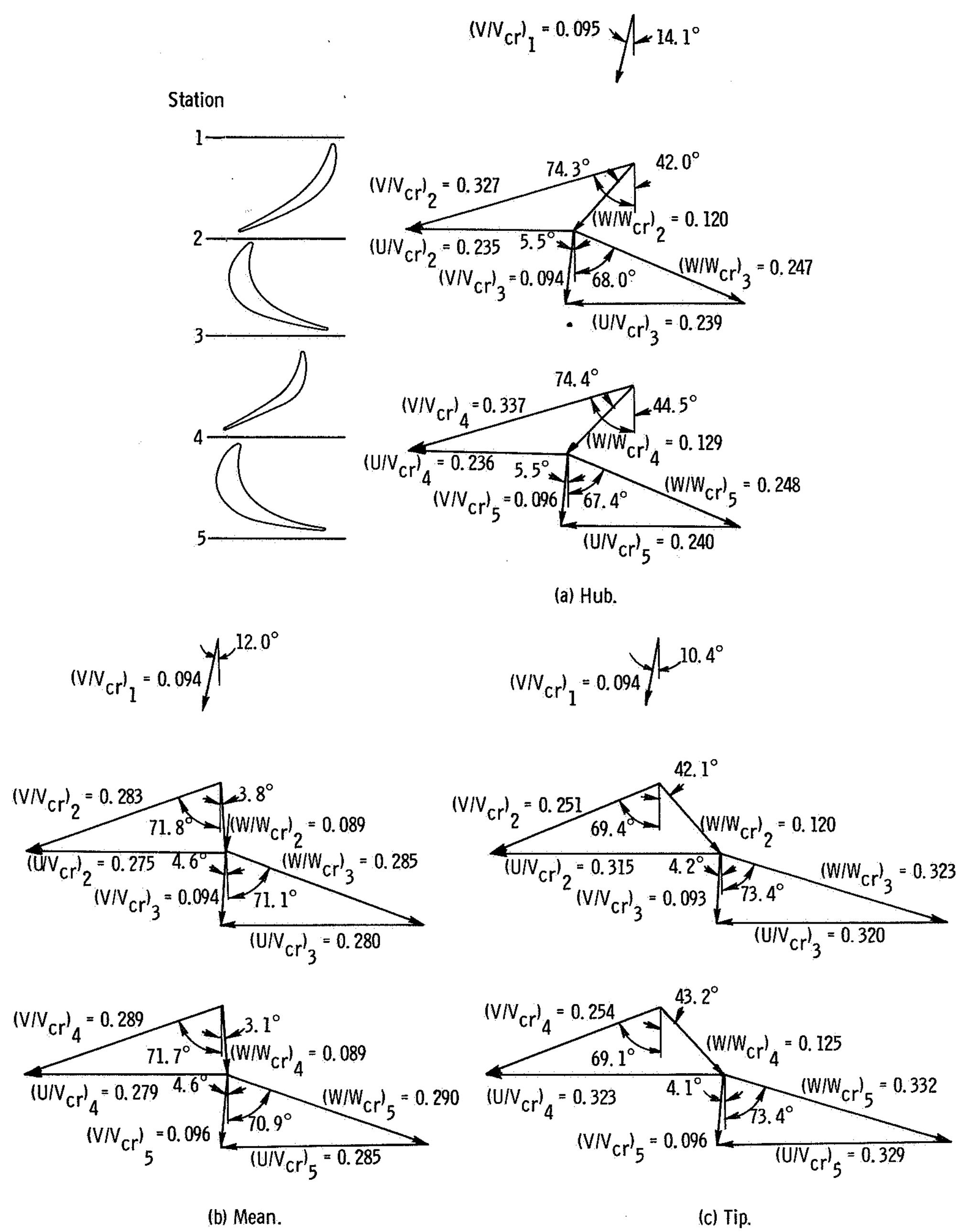

Figure 3. - Design velocity diagrams.

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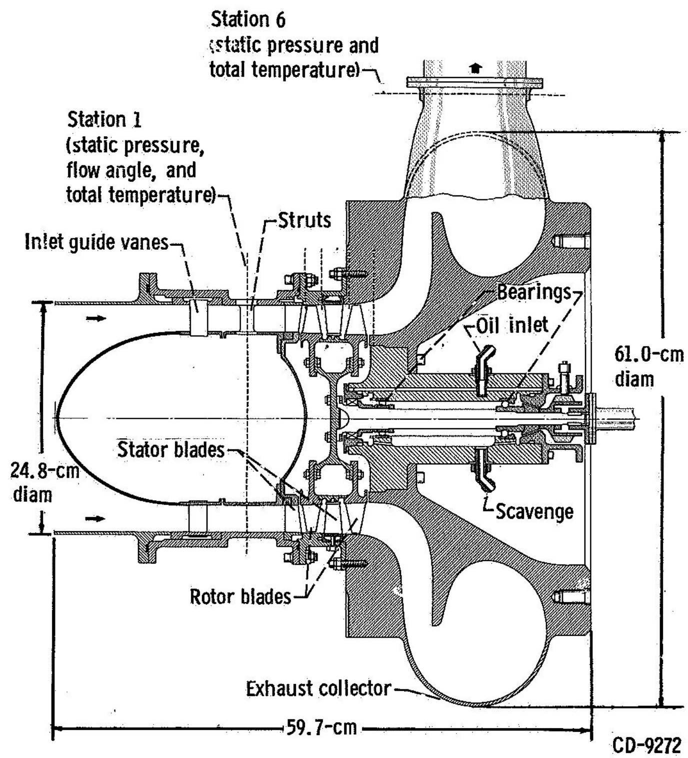


Figure 4. - Cross section of turbine.

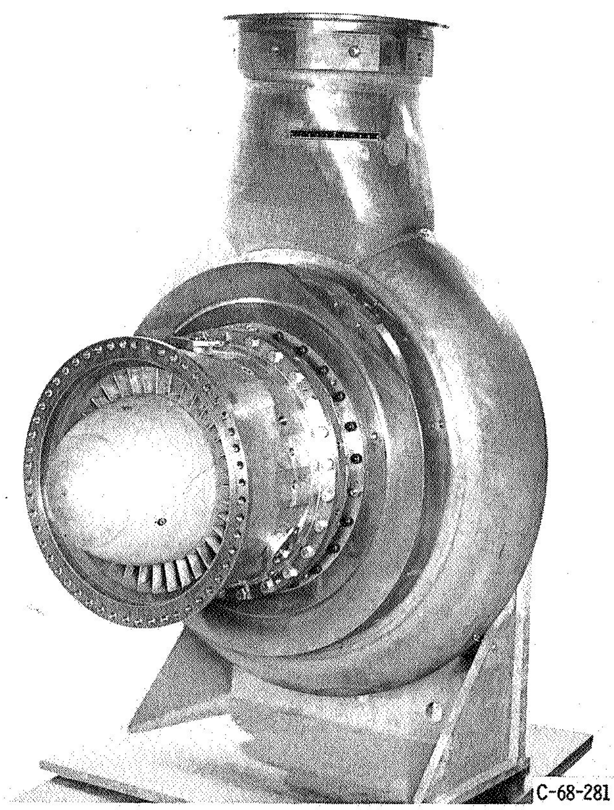


Figure 5. - Turbine assembly.

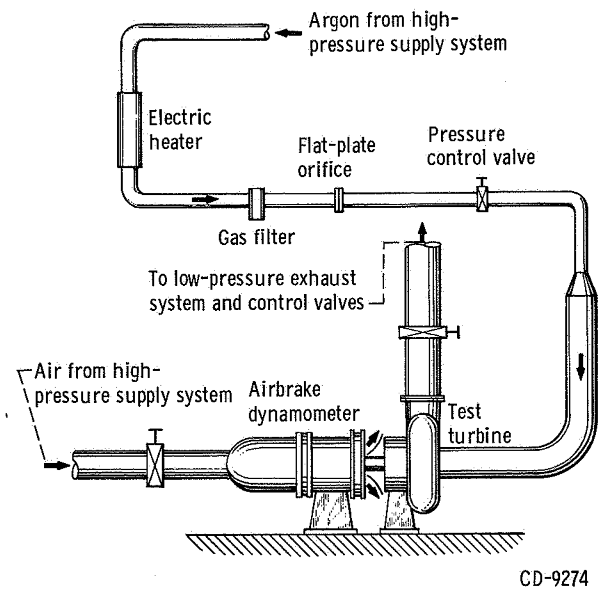
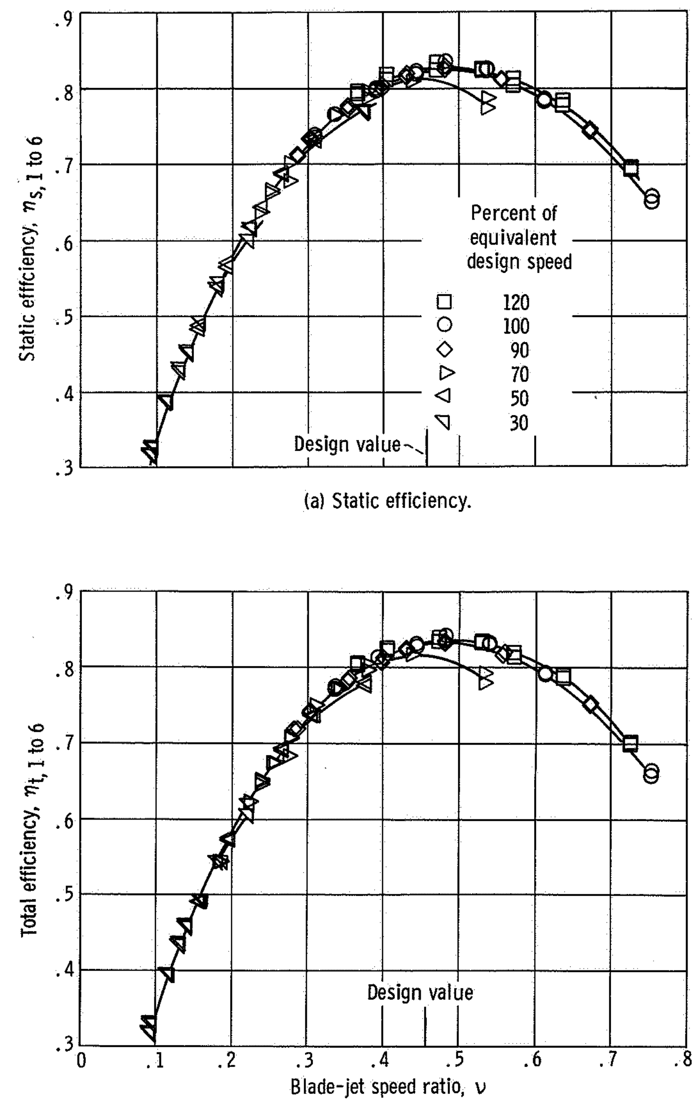


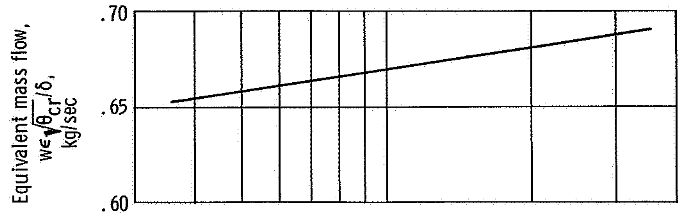
Figure 6. - Experimental equipment.



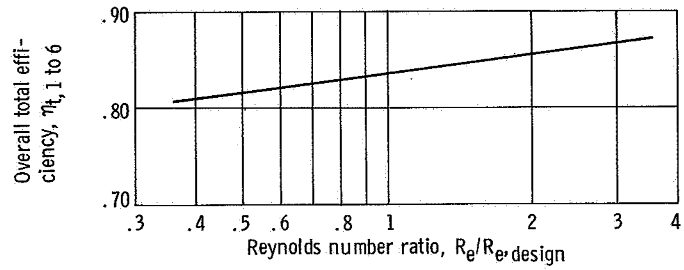
(a) Static efficiency.

(b) Total efficiency.

Figure 7. - Variation of overall efficiency with blade-jet speed ratio for two-stage operation (based on collector-exit conditions).



(a) Equivalent mass flow.



(b) Overall total efficiency.

Figure 8. - Variation of turbine performance with Reynolds number at equivalent design speed and pressure ratio.

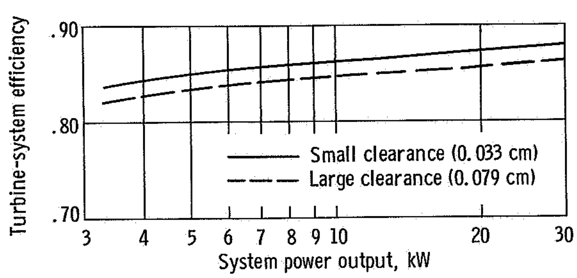


Figure 9. - Turbine system efficiency characteristics.

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